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DIELECTRIC BREAKDOWN IN A DILUTE PLASMA — A 20-KILOVOLT LIMITED STUDY

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16. Abstract

A dielectric breakdown study was made of several materials proposed for high-voltage (16-kV) use on solar-cell arrays at space conditions. The tests were made in an argon plasma whose electron density and temperature approximately simulated conditions at an altitude of 300 km. The maximum voltage used was 20 kV. The results indicate that the breakdown voltages of the materials tested are larger than those quoted in the literature for dielectrics between two metal electrodes.

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DIELECTRIC BREAKDOWN IN A DILUTE PLASMA - A 20-KILOVOLT LIMITED STUDY

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SUMMARY

An experimental dielectric breakdown study has been made of several materials proposed for high-voltage (16-kV) use on solar-cell arrays at space conditions. The dielectrics include Kapton H polyimide film, Teflon FEP, Teflon TFE, Nomex, Mylar A, RTV 511 silicone rubber, Sylgard resin, type 182, quartz 7940 Corning glass, and Parylene C and N. They were tested to determine their dielectric breakdown voltage and capability to withstand several 20-kilovolt pulses of 30-second duration in an argon plasma. The tests were performed at positive bias voltage as high as 20 kilovolts dc relative to ground. The test plasma electron density and temperature approximately simulated conditions at an altitude of 300 kilometers.

The breakdown voltage for each of the dielectrics was higher than those quoted in the literature for cases where two metal electrodes were used. Specimens that did not breakdown at the 20-kilovolt limiting test voltage did not breakdown after the application of six 20-kilovolt pulses.

INTRODUCTION

Recently, solar-cell arrays operating at voltages up to 16 kilovolts have been proposed as power sources in space. Array voltages in this range would be used to operate specialized electronic equipment without the need of heavy power-conditioning systems. In 1968 Cole, Ogawa, and Sellen (ref. 1) demonstrated the need for insulating such high-voltage solar arrays from the electrically active plasma of the space environment at an altitude of 500 kilometers. However, the effects of high voltage on desirable or candidate dielectrics are not well known, and virtually no information is available on their breakdown voltages between a plasma and a metal electrode. Therefore, tests were made to determine these effects on the dielectrics now being considered for this application. The tests were performed at positive bias voltages as high as 20 kilovolts relative to ground in an argon plasma with electron number densities of approximately 10^6 particles per cubic centimeter.

APPARATUS AND PROCEDURE

Facility

The tests were performed in a 0.46-meter-diameter by 0.76-meter-long Pyrex bell jar. The bell jar was mounted on a 0.61-meter-diameter port located on the side of a 3.05-meter-diameter by 4.57-meter-long vacuum tank (fig. 1). The centerline of the bell jar port was 2.29 meters from either end of the vacuum tank. The tank was operated at a vacuum condition of approximately 2×10^{-5} torr. The test specimens were mounted on one end of a 3.2-centimeter-diameter cylindrical Pyrex sting. This passed through and was supported by an instrument ring attached to one end of the bell jar. The high-voltage test location in the bell jar was approximately 2.03 meters from the centerline of the vacuum tank and 7.6 centimeters off the bell-jar centerline. The ammeter used to detect dielectric breakdown and any leakage current preceding breakdown was located between the high-voltage power supply and the test specimen. The wire connecting the test specimen, ammeter, and power supply was shielded, with the shield at the potential of the test specimen. This prevented any leakage current except the dielectric test specimen leakage current from being measured with the ammeter. In all cases the high-voltage probe was biased positive in steps up to 20 kilovolts dc with respect to ground. A 15-centimeter Kaufman ion thruster was used to generate the argon test plasma and was mounted at the center of one of the end caps of the vacuum tank.

Test Specimens

The following dielectrics were tested. They are arranged in groups indicating their function in the design of a solar-cell array (fig. 2).

(1) Solar-cell substrate dielectrics
  (a) Kapton H polyimide film
  (b) Teflon FEP, types A, C, and 20C
  (c) Teflon TFE
  (d) Nomex
  (e) Mylar A
(2) Solar-cell to substrate adhesive: RTV 511 silicone rubber
(3) Solar-cell cover slide to solar-cell adhesive: Sylgard resin, type 182

(4) Solar-cell cover slide: quartz 7940 Corning glass
(5) Insulation (by vapor deposition)
   (a) Parylene C
   (b) Parylene N

Preparation and Mounting of Test Specimens

The following procedure was used to prepare and mount each dielectric specimen on the high-voltage sting shown in figure 3.

(1) A short length of lacquered copper wire was soldered to a copper disk 0.63 centimeter in diameter by 0.025 centimeter thick to make an electrode.

(2) A layer of silver conductive paint was applied to the other surface of each copper disk. While the paint was tacky, a 2.54-centimeter-diameter wafer of test dielectric was placed on the painted surface, to insure a good electrical bond, and allowed to dry.

(3) The exposed side of the copper electrode was then encapsulated with a thick layer of nonconductive epoxy and allowed to dry. This layer was used to help prevent discharges between the plasma and the electrode along the underside of the test dielectric.

(4) The copper lead wire on each specimen was then soldered to a special copper adapter located in the end of the Pyrex sting.

(5) Each specimen-electrode assembly was positioned on the sting as shown in figure 3. A plexiglass mold was then fitted around the sting and filled with Sylgard resin, type 182. When the resin cured, the mold was removed and the specimen was tested.

Plasma Diagnostics

Ions entered the bell jar from the ion thruster beam as a result of scattering collisions. The most probable process was charge exchange collisions with the neutral background gas. This process produces slow ions that can enter the bell jar. The velocity and number density of the ions in the bell jar were estimated by using two cylindrical tungsten Langmuir probes and a Faraday cup. One of the Langmuir probes (25.4 cm long by 0.0254 cm in diameter) was located on the centerline of the tank at the axial station of the port to the bell jar. The other Langmuir probe (12.7 cm long by 0.0127 cm in diameter) was located in the bell jar approximately 20.32 centimeters in front of the test location. A 10.16-centimeter diameter Faraday cup was located about 0.25 meter inside the vacuum tank in front of the bell-jar port. This cup was swung out of the port entrance during tests. The opening for the Faraday cup faced radially into the large vacuum tank.

Velocity. - A potential difference ΔV existed between the ion thruster exhaust beam and the bell jar. This potential difference accelerated the charge exchange ions in the beam radially. The average velocity of the ions was calculated by using this potential difference in the equation

$$v = \left(\frac{2e\,\Delta V}{M}\right)^{1/2} \tag{1}$$

where ΔV is the voltage difference measured between the centerline of the ion thruster beam and the bell jar in the vicinity of the specimen, M is the mass of the ions, and e is the electronic charge. The plasma potential was determined by using standard Langmuir probe techniques as described in reference 2.

Number density. - The plasma number density in the bell jar was found by two independent means. The first method uses the current measured with the Faraday cup I_F and was calculated from the relation

$$n = \frac{I_F}{eAv} \tag{2}$$

where A is the area of the Faraday cup, e is the electronic charge, and v is the velocity of the ions from equation (1).

The second method uses the Langmuir probe in the bell jar. For the expected electron densities in the bell jar and the beam, the Debye length is greater than the probe diameter; therefore, a thick sheath is expected about the Langmuir probe. According to electric probe theory (ref. 2), when there is a thick sheath surrounding a cylindrical electric probe operating in the electron current saturation region and $eV \gg kT$, the square of the current should vary linearly with the applied bias voltage. The number density is related to the slope of this curve by

$$n^2 = \frac{\pi^2}{2A^2e^2}\left(\frac{m}{e}\right)S \tag{3}$$

where S is the slope, A is the probe area, m is the electron mass, and e is the electronic charge. The values found by using these two methods agreed within a factor of 3.

EXPERIMENTAL PROCEDURE

After a specimen was prepared, as described previous, and positioned in the bell jar, the jar was evacuated to a vacuum of approximately 2×10^{-5} torr and allowed to outgas at this condition for at least 30 minutes before the high-voltage test was begun. Voltage was applied in steps of approximately 500 to 1000 volts and held constant for approximately 30 seconds. This procedure was repeated until a limit of 20 kilovolts was reached. The value of leakage current was recorded at each voltage step. If breakdown did not occur at the voltage limit of 20 kilovolts, six 20-kilovolt pulses of approximately 30-second duration was applied to the test specimen. These pulses were applied to determine whether the dielectric would breakdown under a rapidly increasing electric field.

During the tests the plasma floating potential and current density were monitored to ensure steady-state plasma test conditions. After the data for each specimen were obtained, the plasma properties were diagnosed. Finally, the test specimen was removed from the facility. In the case of those specimens which did not break down, the electrical continuity of the high-voltage probe wiring was checked.

RESULTS AND DISCUSSION

All test results were obtained with the specimen at room temperature; they are presented in table I. Shown are the dielectric breakdown voltage, the capability of the dielectric to withstand several 20-kilovolt pulses if breakdown did not occur, and the argon plasma number density. The dielectrics are grouped by headings indicating their function in a solar-cell array design. The term dielectric breakdown voltage is defined in this report as that voltage which exerts sufficient electrical stress across a dielectric to destroy a section of it completely.

During the step application of the voltage, only the Kapton H polyimide film, Parylene C and N, and RTV 511 silicone rubber specimens showed increasing leakage current with increasing voltage. The variation with voltage of these currents preceeding breakdown is shown in figure 4.

The dielectric breakdown voltage of the specimens (table I) is, in most cases, several factors larger than those presented in the literature (ref. 3) for cases where two metal electrodes were used. This difference may be explained by the following considerations. When the plasma is made one of the electrodes, the total voltage drop occurs across the dielectric and some portion of the plasma. Therefore, a larger voltage is required to reach the breakdown strength of the dielectric. Another possible explanation comes from considering the effect of the electric field at the dielectric surface when a metal electrode is placed in contact with it. Asperities of the metal surface can cause the electric field to vary widely over the surface. Therefore, the dielectric adjacent to it may be more susceptible to breakdown than if the metal electrode is replaced with a plasma.

While the applied voltage was being increased until breakdown occurred or until the maximum of 20 kilovolts was reached during a test, some specimens displayed randomly recurrent instantaneous surges of leakage current (of the order of microamperes) during otherwise steady-state conditions. The specimens that showed surges of leakage current were Kapton H polyimide film, Teflon TFE, Teflon FEP, Mylar A, quartz 7940 Corning glass, and Parylene C and N. For these specimens and those that also broke down at a voltage less than 20 kilovolts, the surges tended to become more frequent and their magnitude increased as the applied voltage approached the breakdown voltage. No tests were run to determine the threshold voltages for the beginning of these current surges.

As shown in table I, the 20-kilovolt pulses did not break down any of the specimens which had not broken down during the 20-kilovolt limiting voltage tests. This implies that the rapidly increasing electric field had no measurable effect on the breakdown voltage of the dielectric. The holes after breakdown were irregular in shape, as shown in figure 5, and varied in area up to approximately 0.0048 square centimeter.

The plasma number densities were calculated by using equation (3) and the experimental saturation electron current of the Langmuir probe in the bell jar. These values agree with the number densities determined from the Faraday cup within a factor of 3. The electron temperature determined from the I-V characteristic of the Langmuir probe in the bell jar was approximately 3000 K ($\approx$0.3 eV). The plasma velocity was of the order of 2.4 kilometers per second, which is about one-third the satellite velocity for a 300-kilometer-altitude orbit.

CONCLUDING REMARKS

Various dielectrics (Kapton H polyimide film, Teflon FEP, Teflon TFE, Nomex, Mylar A, RTV 511 silicone rubber, Sylgard resin, type 182, quartz 7940 Corning glass, and Parylene C and N) have been tested to determine their dielectric breakdown voltage and capability to withstand six 20-kilovolt pulses of 30-second duration in an argon plasma. The test plasma electron density and temperature approximately simulated orbital conditions at an altitude of 300 kilometers.

The breakdown voltage for each of the dielectrics tested was higher than values quoted in the literature for these dielectrics between two metal electrodes.

Steady leakage currents occurred during the application of the test voltage for the Kapton H polyimide film, RTV 511 silicone rubber, and Parylene C and N dielectrics. These leakage currents varied inversely with the thickness of the dielectrics. Parylene

C and N showed a leakage current variation with voltage for the 0.0025-centimeter thicknesses only.

Random surges of leakage current of the order of microamperes were observed for Kapton H polyimide film, Teflon FEP, Teflon TFE, Mylar A, quartz 7940 Corning glass, and Parylene C and N. For the specimens that did break down, these current surges became more frequent and intense as the breakdown voltage was approached.

Specimens that did not break down at the 20-kilovolt limiting test voltage also did not break down after six 20-kilovolt pulses were applied.

Within the solar-cell substrate group of materials tested the Teflon FEP specimens displayed higher breakdown voltages than did the Kapton H polyimide film, Nomex, and Mylar A specimens. The Teflon TFE specimens of this group are excluded from this comparison because at the thickness tested they did not break down below or at the 20-kilovolt limiting test voltage. Further, approximately equal values of breakdown voltage were observed for the 0.0051-centimeter-thick specimens of Teflon FEP and those of the insulation group, Parylene C and N. However, leakage currents were observed through the Parylene C and N specimens and none were observed through the Teflon FEP specimens.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 30, 1971,
113-33.

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2. Chen, Francis F.: Electric Probes. Plasma Diagnostic Techniques. R. H. Huddlestone and S. L. Leonard, eds., Academic Press, 1965, pp. 113-200.
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TABLE I. - TEST RESULTS FOR DIELECTRIC SPECIMENS

Specimen	Thickness, cm	Dielectric breakdown voltage, V	Specimen withstood 0- to 20-kV pulses	Plasma number density, particles/cm^3
Solar-cell substrate materials				
Kapton H polyimide film	0.0025	6 400	No	10^6
	.0051	9 000	No	10^6
	.0076	>20 000	Yes	6×10^5
	.0127	>20 000	Yes	10^6
Teflon FEP, type A	0.0051	14 000	No	10^5
	.0127	20 000	No	10^6
Teflon FEP, type C	0.0127	>20 000	Yes	10^5
Teflon FEP, type 20C	0.0051	17 000	No	10^5
	.0051	>20 000	Yes	10^6
	.0051	>20 000	Yes	3×10^5
	.0051	>20 000	Yes	6×10^5
Teflon TFE	0.0127	>20 000	Yes	10^6
	.025	>20 000	Yes	4×10^5
	.055	>20 000	Yes	2×10^5
Nomex	0.0076	8 400	No	10^6
	.0076	9 000	No	10^6
	.0076	8 500	No	2×10^6
	.0127	11 000	No	10^6
Mylar A	0.0076	>20 000	Yes	10^6
	.0127	20 000	No	10^6
	.025	>20 000	Yes	10^6
Solar-cell to substrate adhesive				
RTV 511 silicone rubber	0.0063	2 500	No	2×10^6
	.030	>20 000	Yes	2×10^6
	.051	>20 000	Yes	2×10^6
Solar-cell cover to solar-cell adhesive				
Sylgard resin, type 182	0.048	17 000	No	8×10^5
	.066	>20 000	Yes	10^6
Solar-cell cover slides				
Quartz 7940 Corning glass	0.0076	>20 000	Yes	10^6
Insulation				
Parylene C	0.0025	12 000	No	2×10^6
	.0051	>20 000	Yes	2×10^6
Parylene N	0.0025	12 500	No	10^6
	.0025	14 700	No	10^6
	.0051	16 100	No	2×10^6

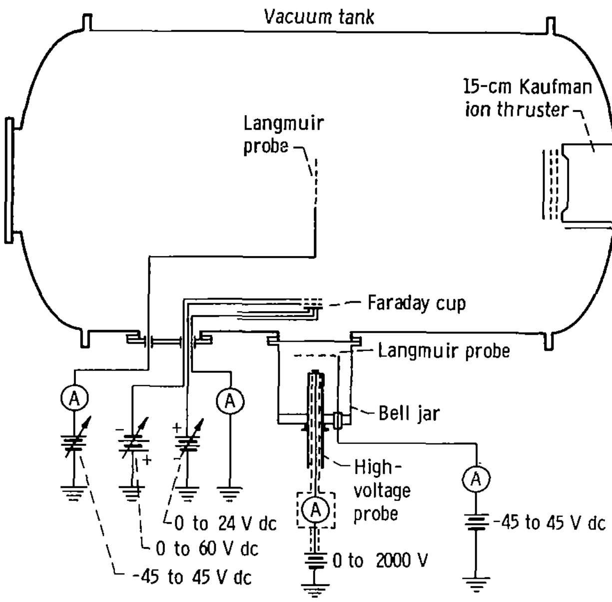


Figure 1. - Sketch of experimental facility. (Not to scale.)

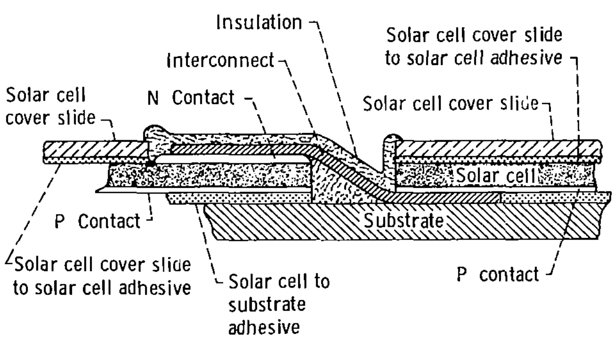


Figure 2. - Cross sectional view of insulated solar cell assembly showing dielectrics.

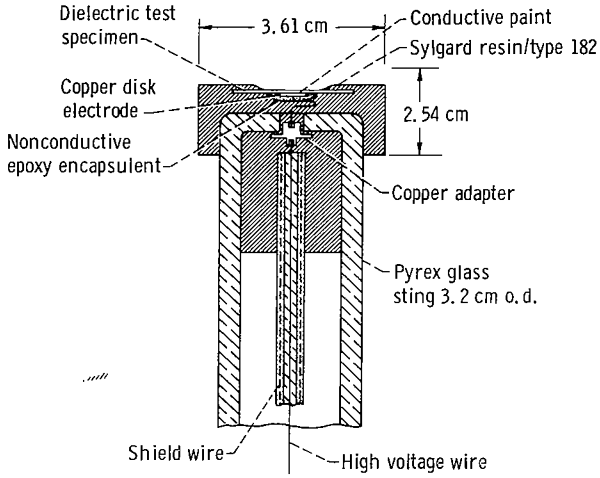
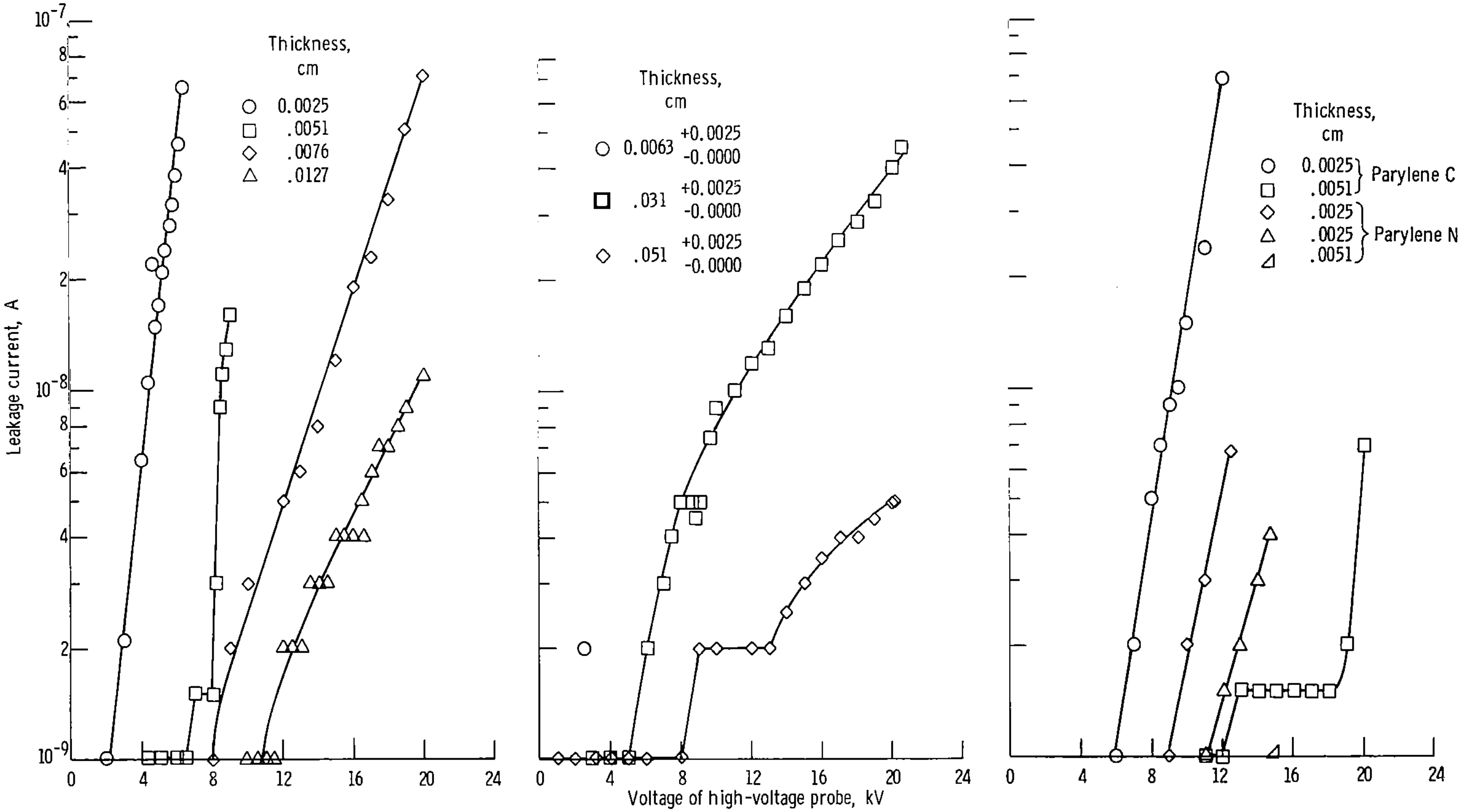


Figure 3. - Cross sectional view of dielectric specimen mounted on end of high voltage pyrex glass sting.



(a) Kapton H polymide film.

(b) RTV 51 silicone rubber.

(c) Parylene C and N.

Figure 4. - Leakage current as function of voltage.

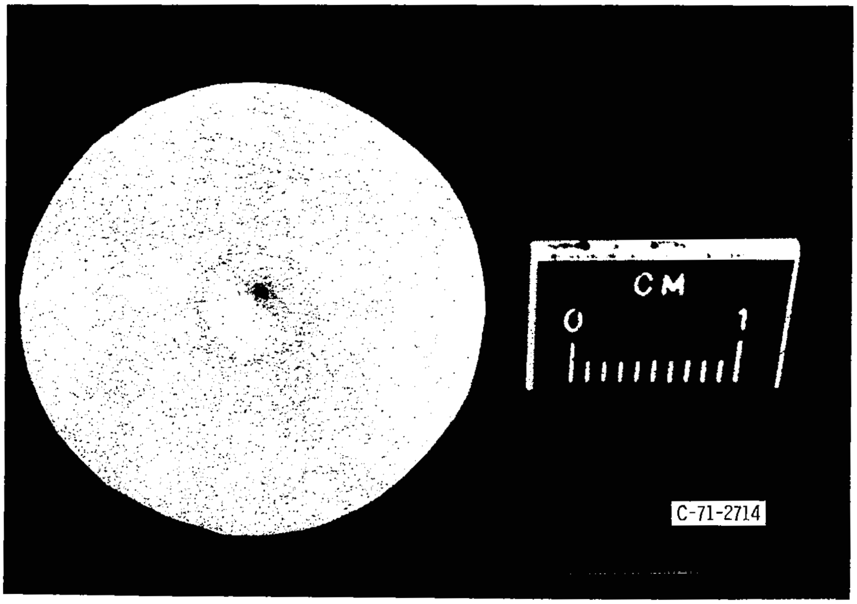


Figure 5. - Typical hole [in Nomex] due to high voltage breakdown.

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